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U. S. DEPARTMENT OF AGRICULTURE.

DIVISION OF SOILS.

AN ELECTRICAL METHOD

OF

DETERMINING THE SOLUBLE SALT
CONTENT OF SOILS,

WITH

SOME RESULTS OF INVESTIGATIONS ON THE EFFECT OF WATER
AND SOLUBLE SALTS ON THE ELECTRICAL
RESISTANCE OF SOILS.

BY

MILTON WHITNEY AND THOS. H. MEANS.



WASHINGTON:

GOVERNMENT PRINTING OFFICE.

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LETTER OF TRANSMITTAL.

U. S. DEPARTMENT OF AGRICULTURE,
DIVISION OF SOILS,
Washington, D. C., March 12, 1897.

SIR: I have the honor to transmit herewith a technical description of an electrical method of determining the soluble salt content of soils. I recommend that it be published as Bulletin No. 8 of this Division.

Respectfully,

MILTON WHITNEY,
Chief of Division.

Hon. JAMES WILSON,
Secretary of Agriculture.

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AN ELECTRICAL METHOD OF DETERMINING THE SOLUBLE SALT CONTENT OF SOILS.

A METHOD OF DETERMINING THE SOLUBLE SALT CONTENT OF SOILS.

A method of salt determination which would show readily and quickly the amount of soluble salt present in the soil and the fluctuations in the concentration of the soil moisture would obviously be of great value in studying the constitution of soils and the relation of the soils to crop production. An electrical method has been devised for this in connection with the electrical method of moisture determination described in Bulletin No. 6.

When a dry soil is moistened with water the minerals and salts in the soil dissolve to a certain extent, forming a salt solution. Some of the salts are so readily soluble that the amount in the soil is not sufficient to make a saturated solution. With the more difficultly soluble salts, however, the small quantities which are dissolved form a really saturated solution so far as these particular compounds are concerned. Any fluctuations in temperature or in the amount of moisture will disturb the equilibrium and induce more of these salts to go into solution or go out of solution as the case may be. Such solutions have certain physical properties, and among them the important property of electrical conductivity. The electrical conductivity depends upon the kind and upon the amount of salt in solution as well as upon the temperature. With the same salt in dilute solutions a solution has approximately twice the conductivity when the salt content is twice as great. With different salts the conductivity is roughly proportional to their molecular weight, or to some simple multiple of this.

As the electrical resistance of soils depends (1) upon the amount of salt solution (soil moisture), (2) upon the concentration of the solution, and (3) upon the temperature, it is possible to determine the soluble salt content of soils from the electrical resistance, provided the temperature and water content are known. On account of the difference in the molecular equivalents of different salts, however, it is necessary to express the quantity in equivalents of some simple salt, such as sodium chloride.

It was desired to perfect a method which would indicate the variations in the soluble salt content in the undisturbed soil of the field, but this has not yet been accomplished, although there is reason to believe it can eventually be done. A very simple and delicate method has, however, been devised for determining the soluble salt content of soils in samples taken from the field. The method consists essentially of mixing a known quantity of soil with a known proportion of pure water and determining the specific resistance. Then an equal weight of the

same soil is mixed with a quantity of a dilute salt solution equal in volume to the pure water which had been mixed with the first quantity of soil. The specific resistance is again determined. This will be lower than before. The amount of salt added to the soil in solution is accurately known, as well as the effect it had on the resistance. From this data the quantity of salt originally present in the soil can readily be calculated in terms of the salt solution used.

DETERMINATION OF THE SPECIFIC RESISTANCE OF SOILS.

The specific resistance of soils as used in this bulletin is the resistance at 60° F. of one cubic centimeter of soil between parallel electrodes one centimeter apart. It is necessary, therefore, in comparing the specific resistance of different soils, or of different samples of the same soil, to give the weight of one cubic centimeter of the soil in order to show how much soil had been packed into this space, or to correct for this packing and reduce the volume in all cases to a unit weight. This may be done by a formula which will be given.

The specific resistance is determined in a hard rubber cell with metal electrodes. The cell is constructed in the following manner: Two heavy brass plates, each one-eighth inch thick, are ground together so that their faces are exactly plane. These are then firmly put together in the form of a cube with hard rubber sides and bottom, the rubber being about three-eighths inch thick. The interior of the cell should be as nearly as possible a cube with lineal dimensions of four centimeters. It must be accurately ground to these exact dimensions, the electrodes must be absolutely parallel, the cell must be water-tight, and the parts very substantially screwed together. The electrodes, as well as the screwheads, should be nickel plated and polished on the outside to prevent corrosion. Heavy copper wires should be soldered to each electrode, and bent so that they will dip into mercury cups as a convenient way of making the necessary connections for taking the resistance. It is convenient to have at least two of these cells, as the work can be done more quickly than with one.

Before use the weight of the cell should be taken, the distance between the electrodes should be very carefully measured, and the actual capacity of the cell should be determined either by measuring in water from a burette or by weighing the quantity of water the cell holds when full. It is essential that the sides be perfectly parallel and all the corners right angles. It is not essential that the inside be cubical. To obtain the specific resistance the observed resistance, when the cell is filled with soil, is multiplied by a constant factor for each cell. This factor is found by dividing the area of the electrodes ($a \times b$) by their distance apart (c). The whole operation would then be:

$$\text{Sp. res.} = R \frac{a \ b}{c}$$

It has been shown in Bulletin No. 6 that when the water content of soils change, either by the addition of water or by its loss through

evaporation, that the actual amount of salt in solution as well as the concentration of the solution is liable to change. It is therefore essential in expressing the salt content of soils to state the water content also. In determining the salt content the method will depend somewhat upon the water content.

By far the easiest and quickest method of determining the soluble salt content is as follows: Measure 10 cubic centimeters of pure water from a burette into one of the hard rubber cells. The water for this as for all such work with soils must be very pure, having a specific resistance of at least 150,000 ohms. Dry soil is then poured into the cell until there is just enough to absorb all the water. The resistance is then measured, the temperature of the soil taken with a thermometer, and the weight of the cell and contents determined. The cell is then thoroughly cleaned and dried and 10 cubic centimeters of a $n/40$ sodium chloride solution is measured into the cell from a burette. The cell is then put in the balance and soil is again poured in until the total weight of the cell and contents is the same as before. The resistance and temperature are again taken. This gives the resistance of a quantity of soil with the same water content, but with a known quantity of salt added to it. This quantity of salt lowers the resistance of the soil to a certain extent. From this a simple proportion will show how much sodium chloride the original soil should have contained to have had the resistance, or rather the conductivity which it was observed to have. The quantity of salt in the soil is thus expressed in terms of sodium chloride.

SOLUBLE SALT IN ONE GRAM OF SOIL.

After the resistance has been corrected for temperature, as will be described later, the weight of soluble salt in milligrams in one gram of soil in sodium chloride equivalents is found by the following formula:¹

$$S = \frac{10s_1 R_1}{(R - R_1) W} .$$

¹ Since for solutions in which the dissociation is complete the conductivity is proportional to the amount of the salt, we have

$$\frac{C}{C_1} = \frac{S_2}{S_2 + 10s_1},$$

where C and C_1 are the conductivities of the soil saturated with distilled water and salt solution, respectively, and S_2 the amount of soluble salt in the weight of soil used.

$$\begin{aligned} \text{But } C &= \frac{1}{R} \text{ and } C_1 = \frac{1}{R_1} \\ \text{Therefore } \frac{R_1}{R} &= \frac{S_2}{S_2 + 10s_1} \\ \text{Solving for } S_2 & \\ S_2 (R_1 - R) + R_1 10s_1 &= 0 \\ \text{or } S_2 &= \frac{R_1 10s_1}{R - R_1} \end{aligned}$$

Since there are W grams of soil used the amount of salt in one gram is

$$S = \frac{S_2}{W} = \frac{10s_1 R_1}{(R - R_1) W}$$

where S = milligrams salt in one gram of soil; s_1 = milligrams salt in 1cc. salt solution; R = resistance of soil saturated with distilled water; R_1 = resistance of same quantity of soil saturated with same quantity of salt solution; W = weight of soil in the cell in grams.

If it is desired to determine the soluble salt content of soil with various percentages of water, short of saturation, the method must be somewhat different and it requires a much larger quantity of soil.

A sufficient quantity of soil, the amount depending upon the range of the investigation, is thoroughly air dried and if at all lumpy is passed through a mill to break down the lumps. It is then well mixed. Equal portions of 500 or 1,000 grams each are weighed out in beakers, two portions for each per cent of moisture it is desired to have in the soil. To one portion of soil a certain percentage of pure water is added, while to a second portion an equal quantity of a dilute sodium chloride solution, preferably $n/40$ or $n/20$, is added. The amount of salt added may either vary with the water or, what is preferable, remain a constant quantity irrespective of the amount of water added. It is usual in this Division to take a quantity of a $n/20$ -salt solution equal to 4 per cent of the dry weight of the soil. This is measured into a beaker from a burette and pure water is added up to the full percentage of moisture which it is desired to add to the soil. One portion only should be moistened at a time to prevent loss by evaporation, but the method of subsequent procedure is precisely the same in both cases.

The moist soil is thoroughly mixed with a Dover's egg-beater, securely fastened to a shelf or table, to distribute the water uniformly throughout the mass of soil. The soil must not be mixed with the hands, as the salts from the hands are liable to vitiate the results, especially in a warm room where the hands are perspiring freely. The soil should be put in a round-bottom bowl or in a heavy glass cover, such as is used in the laboratory to protect apparatus and specimens from dust. With clay soils especially it is well to empty the soil out of the bowl and pour it back again once to insure thorough mixing of the water or solution throughout the mass of soil.

The well-mixed soil is emptied on to a piece of clean oilcloth. One of the hard rubber cells is then filled by putting in small quantities of the soil and pressing it into the corners and down into the cell as firmly as possible with the thumbs. The soil is struck off even with the top of the cell with a spatula. The cell is then placed with its wire electrodes dipping into mercury cups and the resistance taken with an alternating current. The cell and contents are then quickly weighed and the temperature of the soil taken by making a hole in the soil with a pointed instrument and inserting the bulb of a thermometer. After remaining a few moments the temperature is taken. A portion of the soil is then immediately emptied into a flat porcelain or aluminium dish, quickly weighed on a chemical balance, dried for fifteen or twenty hours at a temperature of 110°C ., and the true moisture content obtained

from the loss of weight. Usually three or four determinations are made of the same lot of moist soil and the mean of all taken to find the specific resistance.

CORRECTION FOR TEMPERATURE.

The resistances are all corrected for temperature by reducing them to a uniform temperature of 60° F. by the use of the table at the end of this bulletin. Wherever resistances or conductivities are referred to in this bulletin it will be hereafter understood that they have been corrected for temperature before any further use is made of them. This is the first thing to do after the resistances have been taken, as they can not be compared until this is done.

CORRECTION FOR PACKING.

As it is impossible to pack just the same amount of soil in the cell, in duplicate determinations with the same or with different soils it is usually necessary, in order to compare the results, to correct them all for the difference in packing. This can readily be done by the use of the formula:

$$R_2 = \frac{W^2 R}{W_1^2},$$

where R_2 = resistance if the cell contained a unit weight of soil; R = observed resistance; W = actual weight of soil contained in cell; W_1 = unit weight of soil (usually 100 grams for a cell of the dimensions given above).

SALT ADDED TO ONE CUBIC CENTIMETER OF SOIL.

The salt added to the soil by the salt solution lowers the resistance of the soil considerably. The actual amount of salt added to one cubic centimeter of soil in the cell is calculated by the following formula:

$$S_1 = \frac{W}{V} p_1 s_1,$$

where S_1 = milligrams of salt added to one cubic centimeter of soil by the salt solution used; s_1 = milligrams of salt in one cubic centimeter of salt solution; W = grams of soil in cell; V = volume of cell; p_1 = per cent of salt solution of given strength added to the soil.

SOLUBLE SALT IN ONE CUBIC CENTIMETER OF SOIL.

Having determined the amount of salt added to the soil by the salt solution and the extent to which it has lowered the resistance, the amount of salt originally present in the soil may be calculated by a simple proportion in terms of sodium chloride. The proportion is expressed in the following formula:

$$S_2 = \frac{S_1 R_1}{R - R_1},$$

where S_2 = milligrams of salt in one cubic centimeter of natural soil in terms of sodium chloride; S_1 = milligrams of salt added to one cubic centimeter of soil by means of the salt solution; R = resistance of natural soil; R_1 = resistance of the soil to which salt solution has been added.

SALT IN ONE CUBIC CENTIMETER OF SOIL MOISTURE.

Knowing the weight of soluble salts in sodium chloride equivalents contained in one cubic centimeter of soil, it is a simple matter to calculate the amount of salt in one cubic centimeter of soil moisture which will give the concentration of the salt solution in the soil. This is done by the formula:

$$s = \frac{S}{W_1 p},$$

where s = milligrams of salt in one cubic centimeter of soil moisture expressed in terms of sodium chloride; S = milligrams of salt in one cubic centimeter of natural soil; W_1 = weight of one cubic centimeter of soil calculated from the total weight of soil and volume of the cell; p = the per cent of water in the soil. One cubic centimeter of $n/20$ sodium chloride solution contains 2.918 milligrams of salt.

SALT CONTENT OF SOILS OF SAME TEXTURE.

When samples of soils of the same texture are to be used for a series of investigations the method can be shortened considerably as it is only necessary to accurately determine the salt content once, together with the specific resistance. Thereafter it will only be necessary to determine the specific resistance of the soils and, if the soils are saturated with water, or, when short of saturation if a correction is made for packing and the water content is the same, the amount of salt can be calculated by the formula:

$$S_a = \frac{R S_2}{R_a},$$

where S_a = salt content to be determined; R = specific resistance with known salt content; R_a = specific resistance with unknown salt content; S_2 = salt content corresponding to specific resistance R .

DEFINITION OF TERM "SODIUM CHLORIDE EQUIVALENT."

It has been stated that the electrical molecular conductivity of different salts in solution is roughly proportional to their molecular weight or some simple multiple of the same. As it is not possible to distinguish the different salts as they occur mixed in the soil moisture by their electrical properties, it is necessary to estimate the total quantity of salts present in solution in terms of some well-known salt easily obtainable in a pure state and which will keep in an ordinary aqueous solution without deterioration or change. For this purpose sodium chloride has been selected as the standard of measurement in the inves-

tigations in this Division. The quantity of other salts in solution is expressed in terms of sodium chloride equivalents. A sodium chloride equivalent may be defined as the quantity of a salt which has the same electrical conductivity as a unit weight of sodium chloride when dissolved and diluted to the same volume.

Owing to the difference in molecular weight of different salts, in the number of ions formed through dissociation, and in the ionic velocities this quantity will not have a constant value. The following results, calculated from the investigations of Kohlrausch, give the approximate

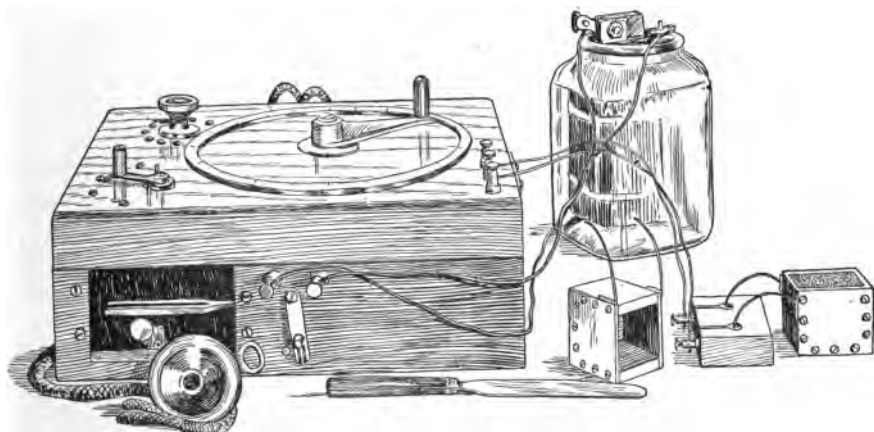


FIG. 1.—Bridge box with cells used in determining the soluble salt content.

relative weights of some of the most common salts which, under the above conditions, have a conductivity equal to sodium chloride:

NaCl	1
KCl	1.07
K ₂ SO ₄	1.21
KNO ₃	1.49
NaNO ₃	1.55

THE MEASUREMENT OF THE ELECTRICAL RESISTANCE.

The electrical resistance is measured by the Wheatstone bridge method, with an alternating current to prevent polarization and a telephone in place of a galvanometer. The measurements may be made with a slide-meter bridge or a suitable box of coils. The portable bridge box, described in Bulletin No. 6, is a very convenient form for laboratory or field use. The construction and use of the box is described in the bulletin. The bridge box, with one of the hard rubber cells in position, with electrodes dipping into mercury cups as in the actual salt determinations, is shown in the accompanying figure (1).

SOLUBLE SALT CONTENT OF SEVERAL SOILS.

The accompanying table gives the soluble salt content of a number of soils determined by this method, both when the soils are saturated with water and with different percentages of water in some of them:

Soluble salt content of soils saturated with water.

[In sodium chloride equivalents.]

No. of samples.	Kind of soil.	Formation.	Salt content.	
			In 100 grams.	In one acre.*
3	Bright tobacco, North Carolina.		<i>Mg.</i> 4.27	<i>Lbs.</i> 171
1	Red land, South Carolina.	Lafayette.	4.95	198
24	Truck, Maryland.	Columbia.	5.84	234
12	Dark tobacco, Virginia.	Gabbro, gneiss.	6.76	270
1	Corn, wheat, Maryland.	Gabbro.	12.75	510
1	Corn, Maryland.	Trenton limestone.	14.04	562
6	Loess, Nebraska.	Loess.	15.69	628
19	Grass, Maryland, Virginia.	Trenton limestone.	16.44	650
1	Sea-island cotton, South Carolina.		22.36	894
1	Wheat, Maryland.	Chesapeake.	25.33	1,013
1	Wheat, grass, Maryland.	do.	27.46	1,098
1	Tobacco, Pennsylvania.	Shaly limestone.	31.30	1,252
15	Plains soil, Kansas, Nebraska.		34.87	1,395
1	Blue grass, Kentucky.	Trenton limestone.	37.04	1,482
1	Loess, Illinois.	Loess.	45.28	1,811
1	Plains marl, Nebraska.	Plains marl.	45.71	1,828
1	Wheat, Maryland.	Trenton limestone.	59.69	2,388
1	Grass, Maryland.	do.	62.23	2,489
1	Stiff clay, Virginia.	do.	83.56	3,342

* The soil is assumed to weigh 4,000,000 pounds per acre, one foot deep.

Specific resistance and soluble salt content of soils short of saturation.

Water.	Weight 1 cc. soil.	Specific resistance.	Salt in 100 g. soil.	Salt in 10 cc. soil moisture.
BRIGHT-TOBACCO LAND, NORTH CAROLINA.				
<i>Per cent.</i>	<i>Grams.</i>	<i>Ohms.</i>	<i>Mg.</i>	<i>Mg.</i>
18	1.54	34,260	3.03	1.68
15	1.54	40,300	3.20	2.13
12	1.54	57,430	3.17	2.62
9	1.54	111,830	3.77	4.19
7	1.54	191,400	3.21	4.59
"HEAVY" LOAM, MARYLAND.				
21	1.54	9,790	11.73	5.58
18	1.54	12,260	12.88	7.16
15	1.54	19,655	11.08	9.23
12	1.54	33,930	9.87	8.22
9	1.54	73,968	11.16	12.40
LOAM, MARYLAND.				
21	1.54	6,854	12.54	5.97
18	1.54	7,758	14.53	8.07
15	1.54	9,688	17.41	11.61
12	1.54	13,990	19.47	16.23
9	1.54	22,914	28.65	31.84

Specific resistance and soluble salt content of soils short of saturation—Continued.

Water.	Weight 1 cc. soil.	Specific resistance.	Salt in 100 g. soil.	Salt in 10 cc. soil mois- ture.
SEA-ISLAND SOIL, SOUTH CAROLINA.				
<i>Per cent.</i>	<i>Grams.</i>	<i>Ohms.</i>	<i>Mg.</i>	<i>Mg.</i>
15	1.38	4,360	37.94	25.29
12	1.36	5,600	35.57	29.64
9	1.34	8,050	29.92	33.25
6	1.33	21,000	24.01	40.01
LOESS, ILLINOIS.				
18	1.47	4,631	30.49	17.00
15	1.45	5,478	31.66	21.10
12	1.42	6,399	36.99	30.70
9	1.40	8,009	42.97	47.60
7	1.39	10,051	60.12	86.00

As a rule, the amount of soluble salt is greatest in the heavy clay soils, but this is not always so. The sandy bright-tobacco and truck soils have the least, while the heavy clay, gabbro, and gneiss soils of Virginia, the so-called "worn-out tobacco lands," have hardly more. Some of the other soils have eight or ten times as much. Where the different percentages of water are added to the soils, the concentration of the solution decreases with the increase of water. In one case the amount of salts in solution increases with the amount of water, in two cases it decreases, while with the remainder of the soils it is fairly constant.

These investigations were all made with air-dried laboratory samples of subsoil which had been collected under various conditions of climate, season of the year, and cropping. It would be of great value to make a systematic study of the soluble salt content of representative soils at frequent intervals throughout the year, with special reference to the character of the season and cropping and at several stated depths below the surface.

One very important matter which has been brought to light during the course of the investigations is that very slight changes of conditions have a very marked influence on the solubility of the soil constituents. Thus, if the soil is dried at 110° C., as in the ordinary moisture determination, the amount of salts which will go into solution in pure water is frequently increased 100 per cent.

In considering the nature of the soluble salts in the soil it must be remembered that the capillary spaces in the soils are so small, and the films of moisture around the grains in a soil short of saturation are so extremely thin, that the fluid loses the properties of a liquid in mass. The most striking property of the soil moisture, as considered in the light of a salt solution, is that part of the salts of the soil may be in solution and yet not be readily washed out.

Some quite dry soil was put into a cell with metal electrodes and leached by a constant stream of pure water. The accompanying table shows that the resistance fell enormously on saturating the soil, but on

continuing the flow the leachable salts were quickly carried out, the resistance increasing until, with these two soils, it was five times as much as when first saturated, when it remained constant. Approximately four-fifths of the salts were leachable and one fifth were non-leachable, and while they were in solution and were dissociated in the soil they could not readily be washed out.

Experiments on leaching soils.

A.		B.	
Time.	Resistance.	Time.	Resistance.
<i>Min.</i>	<i>Ohms.</i>	<i>Min.</i>	<i>Ohms.</i>
Initial.	77,000	Initial.	85,000
0	500	4	1,600
3	670	17	410
20	1,150	20	600
28	1,840	28	1,050
45	1,970	46	1,400
85	2,390	85	1,950
121	2,370	122	1,990
194	2,450	194	1,780
217	2,690	217	2,200
239	2,690	239	2,270
265	2,650	265	2,270

Soils have what may be called a solution constant; that is, after all the readily soluble salts have been removed the other constituents of the soil continue to be slowly dissolved for a very long time. It is a very difficult thing, therefore, to determine the solubility of a soil either in water or other solvents.

A quantity of a soil was mixed with twice its volume of distilled water and well shaken. Then half of the solution was poured off and replaced by an equal quantity of distilled water. This was repeated, the resistance of each portion being taken as it was poured off. If no dissolving action had been taking place, the process would have resulted in a simple dilution of the soluble salt already present, and the resistance of each portion would have been approximately twice that of the preceding portion. The following results indicate the continuous solution of the soil salts:

	Ohms.
Initial resistance.....	1,185
After first replacement.....	1,545
After second replacement.....	2,130
After third replacement.....	2,830
After fourth replacement.....	2,830
After fifth replacement.....	3,420
After sixth replacement.....	3,920
After seventh replacement.....	4,900
After eighth replacement.....	5,400
After ninth replacement.....	8,000
After standing twenty-four hours.....	3,250

Even with purified quartz sand (glass sand) which had been digested with acids and alkalies and thoroughly washed there was a slow solution. To a quantity of the sand was added a small amount of pure sodium chloride and some pure water in a flask of Jena glass. This

was shaken several times a day and the resistance of the solution determined daily with the following results:

	Ohms.
Resistance, initial	1,587
Resistance after three days	1,167
Resistance after six days	1,159
Resistance after nine days	1,153
Resistance after fourteen days	1,143
Resistance after seventeen days	1,112
Resistance after twenty days	1,089
Resistance after twenty-three days	1,090

Some of the same solution in a similar flask without the sand showed practically no change during this time. Natural soils show the same gradual increase in solubility, except that in a few cases the resistance has been noticed to go up for a few days as though salts were going out of solution, usually to fall again on longer standing.

In such digestion experiments great care must be taken to secure extremely insoluble glass. The ordinary Bohemian glassware, such as is used for measuring flasks in chemical laboratories, is liable to be quite soluble and entirely unsuited to this work. Thus some flasks which had been thoroughly steamed and cleaned with acids and alkalis and washed were filled with water having a specific resistance of 148,000 ohms. The water was then immediately emptied from the flasks and the resistance taken. It was then replaced and the flasks heated for three hours in a steam bath. They were then allowed to stand forty hours, when the resistance was again taken, with the following results:

No. of flask.	Resistance.	
	Initial.	After steam- ing.
(Water used)	148,000	-----
1.....	110,000	13,000
2.....	82,900	1,020
3.....	77,000	15,000
4.....	119,000	8,450
5.....	115,000	1,550
6.....	93,000	1,420
7.....	100,000	3,100
8.....	66,300	1,650

The resistance of a $n/300$ sodium-chloride solution is about 1,500 ohms.

On the other hand, common glass bottles are often highly insoluble, and high-grade water even improves on standing in them. It is necessary, before any work on the solubility of soils is undertaken, to actually test the solubility of all the glass used.

If a convenient method is devised for determining the soluble salt content of soils in the field by electrodes buried at different depths, as is now done in the case of water, it will undoubtedly show that the soluble salts are constantly fluctuating with changing conditions, sometimes more salts going into and at other times more salts going out of solution. It is needless to say that such a line of investigation, with

a method which can be relied upon to detect variations of a thousandth of a milligram of soluble salt in a gram of soil, is of the utmost importance in studying the fundamental problems of cultivation, fertilization, and rotation of crops.

THE INFLUENCE OF WATER AND OF SOLUBLE SALTS ON THE ELECTRICAL RESISTANCE OF SOILS.

Investigations along these lines throw an important light upon the chemical and physical constitution of soils. Furthermore, it was necessary to thoroughly investigate the influence of water and salts on soils in connection with the method of moisture determination described in Bulletin No. 6.

INFLUENCE OF MOISTURE ON THE ELECTRICAL RESISTANCE OF NATURAL SOILS.

The method of procedure is the same as for salt determinations already described, except that no salt solution is used. Equal quantities of the soil are thoroughly mixed with 5, 6, and so on, up to 25 or 35 per cent by weight of water. The specific resistance is determined in the hard rubber cell, and when the actual moisture determination and corrections for packing and temperature are made the results are plotted on cross-section paper of large scale and a curve drawn through the points of observation. The resistance for each whole per cent of water is then picked out from this curve.

As the specific resistance of the different soils varied greatly, owing to the difference in salt content, they were all reduced to some common basis. With soils in which the moisture naturally varies in the field from 5 to 20 per cent the resistance with 10 per cent is taken to equal 1,000, and all the other resistances are reduced in the same proportion. With soils in which the moisture ranges from 10 to 25 per cent the resistance with 15 per cent is taken to equal 1,000. These reduced readings give the rate of change of resistance with changing water, and the curve is called a ratio curve.

The accompanying tables give the specific resistance, specific conductivity, and rate of change of resistance with changing moisture of a number of soils:

Specific resistance and conductivity of soils.

[Conductivity multiplied by 10,000.]

Per cent moisture.	Truck land.		Sea-island cotton land.		Bright tobacco land.		Loess.	
	Resistance.	Conductivity.	Resistance.	Conductivity.	Resistance.	Conductivity.	Resistance.	Conductivity.
15	-----	-----	4,367	2.291	8,660	1.155	5,478	1.826
14	-----	-----	4,731	2.114	9,510	1.052	5,768	1.734
13	4,060	2.463	5,145	1.944	11,640	0.859	6,059	1.650
12	4,210	2.375	5,602	1.785	12,190	0.821	6,399	1.563
11	4,480	2.232	6,183	1.617	14,600	0.685	6,764	1.478
10	5,150	1.942	6,971	1.435	18,030	0.555	7,284	1.373
9	6,600	1.515	8,052	1.242	22,700	0.441	8,009	1.249
8	8,800	1.136	9,752	1.026	30,220	0.331	8,943	1.119
7	12,200	0.820	12,680	0.789	41,310	0.242	10,051	0.995
6	16,200	0.617	21,000	0.476	-----	-----	11,338	0.882

Ratio of change of resistance with changing moisture content.

Per cent moisture.	Truck land.	Sea-land cotton.	Bright tobacco.	Loess.
16	-----	571	-----	713
15	-----	621	627	752
14	-----	674	679	791
13	788	734	738	832
12	818	790	804	879
11	870	882	887	928
10	1,000	1,000	1,000	1,000
9	1,252	1,148	1,155	1,097
8	1,709	1,391	1,399	1,227
7	2,369	1,806	1,820	1,380
6	3,147	2,994	3,013	1,557

Specific resistance, conductivity, and ratio of two loam soils from Maryland.

[Conductivity multiplied by 10,000.]

Per cent moisture.	Loam.		Heavy loam.		Ratio.	
	Resist- ance.	Conduc- tivity.	Resist- ance.	Conduc- tivity.	Loam.	Heavy loam.
20	7,261	1.377	10,790	0.927	726	560
19	7,595	1.317	11,620	0.860	760	603
18	8,090	1.236	12,660	0.790	800	657
17	8,549	1.170	14,010	0.714	855	727
16	9,170	1.090	16,140	0.620	917	838
15	10,000	1.000	19,250	0.518	1,000	1,000
14	11,100	0.900	23,240	0.430	1,110	1,207
13	12,570	0.796	28,531	0.350	1,257	1,482
12	14,440	0.693	35,010	0.285	1,444	1,819
11	16,720	0.598	42,940	0.233	1,671	2,230
10	19,790	0.505	55,400	0.180	1,979	2,877

It will be seen from the tables that the resistance varies greatly with the amount of moisture. It is upon this great change in resistance that the method for the determination of the water content of soils, described in Bulletin No. 6, is based. Thus, between 6 and 12 per cent of moisture the resistance of the truck land varied about 12,000 ohms, while the measuring apparatus is accurate to at least 10 ohms below 5,000 and 100 ohms between 5,000 and 50,000. The specific resistance of different soils varies greatly with the same percentage of moisture, partly due to the difference in salt content and partly, as will be shown, to the difference in texture of the soils.

The ratio curve shows that water does not have the same influence on the resistance of all soils. It requires from 1 to 3 per cent more water to produce the same change in the resistance of some soils than in others. Part of this is due to the difference in the amount of salt in solution with the different per cents of water, but this difference in the solubility of soils does not account for it all. When the actual resistances are plotted they make smooth curves, and when the relative resistances are plotted it is seen that the curves for different soils while regular and approximately of the same order have a different slope. They agree in the main with an hyperbolic curve except that they are more or less rotated. This difference in slope seems to be characteristic of the different soils.

The conductivity corresponding to the hyperbola curve gives a straight line when plotted. The conductivities of these soils give ap-

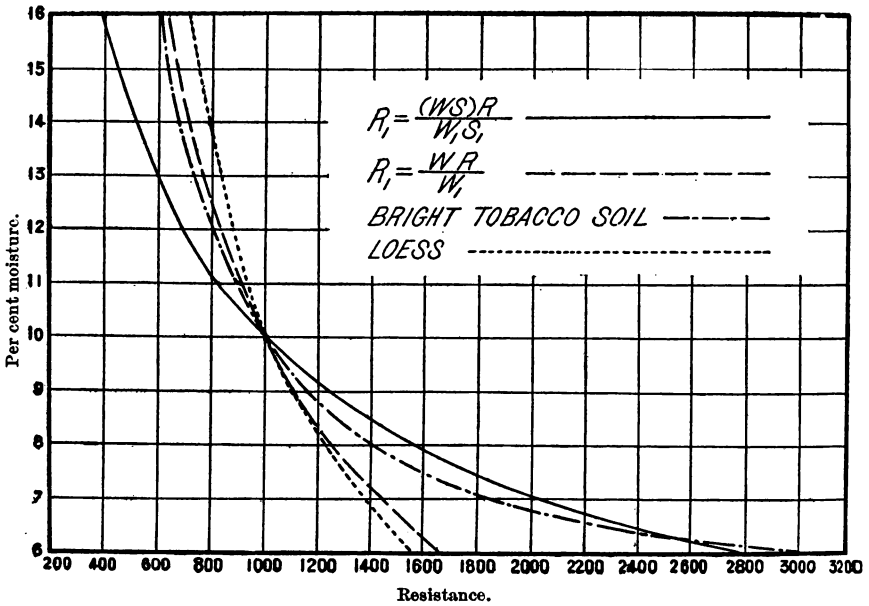


FIG. 2.—Resistance-moisture curves of loess and bright tobacco soils.

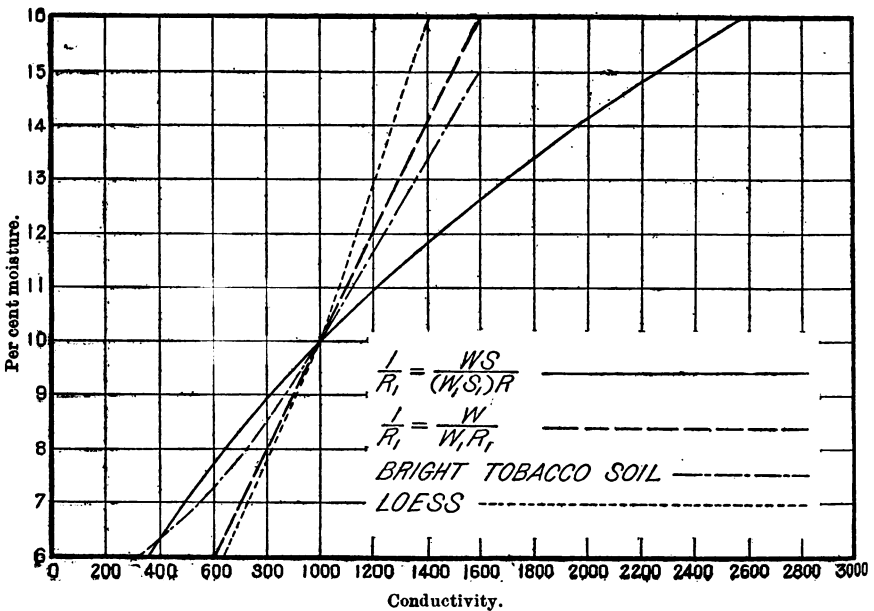


FIG. 3.—Conductivity-moisture curves of loess and bright tobacco soils.

proximately straight lines with different inclinations as compared with the hyperbola. This makes it easier in some respects to deal with the

conductivities than with the resistances, as each percentage of water has about the same value in conductivity units whether the soil is wet

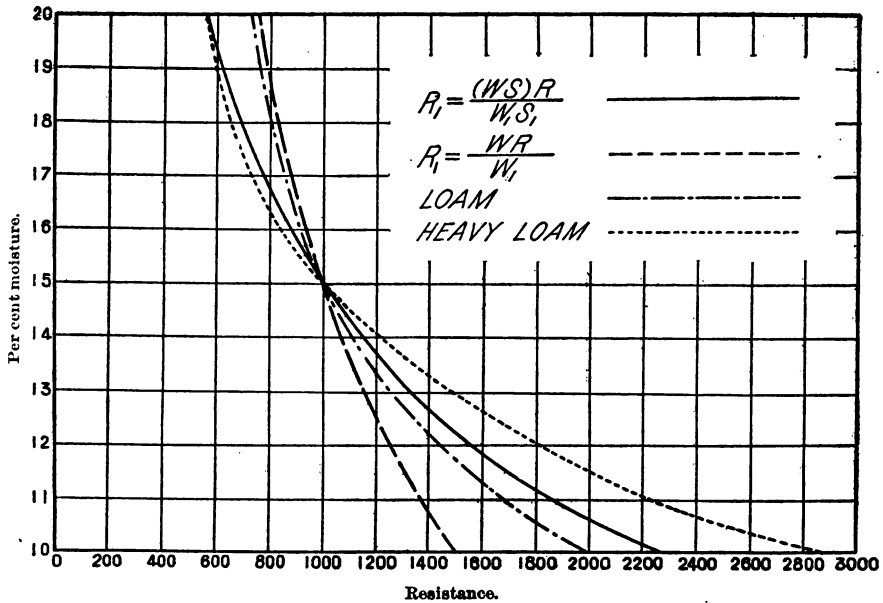


FIG. 4.—Resistance-moisture curves of two loams from Davidsonville, Md.

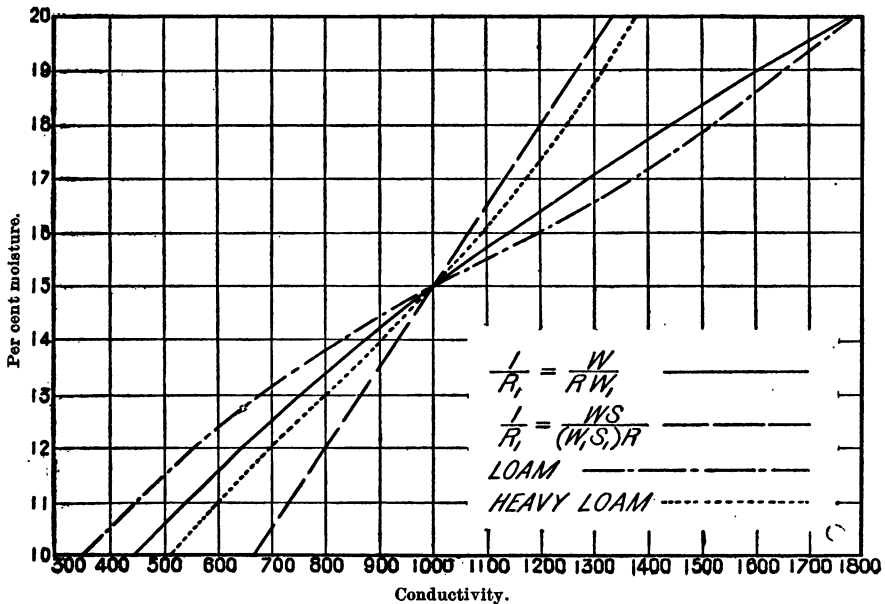


FIG. 5.—Conductivity-moisture curves of two loams from Davidsonville, Md.

or dry, while it has very different values in resistance. A table of reciprocals for calculating the conductivity from the resistance is given in Bulletin No. 6.

The accompanying figures (2, 3, 4, 5) show the conductivities of these different soils, together with the reciprocals of two hyperbolic curves.

If the curves were the same as the hyperbola $R = \frac{W R}{W}$, then the conductivity would vary directly with the amount of moisture. If it followed the other hyperbola the resistance would vary as the square of the moisture content.

RESISTANCE OF SALT SOLUTION ABSORBED IN PURE QUARTZ SAND.

In order to study further in regard to the electrical properties of soils, an artificial soil was made up of pure quartz sand and salt solutions of various strengths. The sand (glass sand) was thoroughly purified by digesting in hydrochloric acid, carbonate of soda, and by repeatedly washing with pure water until the specific resistance of the wash water was at least 200,000 ohms. Equal quantities of this sand were then thoroughly mixed with 5, 6, 7, and up to 19 per cent of different strength salt solutions, and the specific resistance of the moist sand was determined by use of the hard-rubber cell. The results are given in the accompanying table.

Resistance of salt solution absorbed in pure quartz sand.

Per cent moisture.		Specific resistance.					Ratio 10 per cent = 1,000.					
		$\frac{n}{20} K_2SO_4$.	$\frac{n}{10} NaCl$.	$\frac{n}{20} NaCl$.	$\frac{n}{40} NaCl$.	$\frac{n}{20} K_2SO_4$.	$\frac{n}{10} NaCl$.	$\frac{n}{20} NaCl$.	$\frac{n}{40} NaCl$.	Mean.	$R_s = \frac{(WS) R_s^*}{W S_s}$.	Salt constant.
19.....	1,079	1,058	2,075	4,150	260	264	277	266	267	277	507	526
18.....	1,232	1,120	2,303	4,565	297	280	307	292	294	309	529	555
17.....	1,398	1,245	2,614	5,063	337	311	349	324	330	346	561	588
16.....	1,577	1,432	3,008	5,644	380	357	402	362	375	390	600	625
15.....	1,784	1,681	3,485	6,340	430	420	465	406	430	444	645	666
14.....	2,075	1,992	4,046	7,262	500	497	540	465	500	510	700	714
13.....	2,378	2,365	4,689	8,432	573	591	628	553	588	592	769	782
12.....	2,768	2,802	5,437	10,458	667	700	726	664	689	695	827	833
11.....	3,349	3,319	6,340	12,740	807	829	847	816	825	826	907	909
10.....	4,150	4,000	7,491	15,604	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
9.....	5,329	5,023	9,378	18,675	1,284	1,254	1,252	1,200	1,247	1,235	1,122	1,111
8.....	7,001	6,494	12,180	24,070	1,687	1,622	1,626	1,540	1,619	1,593	1,295	1,250
7.....	9,171	8,632	16,600	32,702	2,210	2,155	2,116	2,100	2,170	2,041	1,519	1,444
6.....	12,313	11,740	21,580	45,650	2,967	2,933	2,881	2,920	2,925	2,777	1,755	1,666
5.....	17,015	17,110	31,540	65,196	4,100	4,275	4,210	4,180	4,191	4,000	2,085	2,000

* The salt varies directly as the water. The resistance agrees with the curve represented by the equation $R_s = \frac{(WS) R}{W S_s}$, where R_s = resistance with unit quantity of water; R_s = resistance with any other quantity of water; W = unit quantity of water (10 per cent in this case); S = salt with unit quantity of water; S_s = salt content with any other quantity of water.

† The salt is constant, while the water alone varies. The resistance agrees with the hyperbolic curve and the equation would be $R_s = \frac{W R}{W_s}$.

It is seen that the resistance is very nearly inversely proportional to the amount of salt. The resistance of the $n/20$ solution is very nearly half the resistance of the $n/40$ and approximately twice that of the $n/10$, although here the effect of the greater dissociation in the dilute solutions is apparent. The resistance of the $n/20$ potassium sulphate solution is about equal to the $n/10$ sodium chloride solution. This is because the sulphate ion carries a double electric charge, so that the solution has twice the conductivity of a solution of sodium chloride of the same number of salt equivalents. From the second part of the table it is seen that notwithstanding the differences in actual resistance, the rate of change is about the same for the different salts and the different strengths of salt solutions. This rate of change seems to be independent of the nature of the salt or of the strength of the solution in the case of sodium chloride, potassium sulphate, potassium nitrate, and acid potassium phosphate. The mean results show that when the amount of the salt solution is double and there is twice as much water and twice as much salt present, the resistance is about one-fourth. If the water alone is doubled, while the salt remains constant, the resistance will be one-half. On the other hand, when there is one-half as much solution, so that there is half as much water and half as much salt, the resistance is four times as great, while if there is half as much water and the same quantity of salt the resistance is twice as great. Where the salt and the water change in the same proportion the resistances when plotted agree with one hyperbolic curve and the resistance, or the water, or the salt can be calculated for any part of the curve if any two of the values are known. Where the salt is constant and the water alone changes, the resistance agrees with another hyperbola and the conductivities would form a straight line. This may be taken as the basis in studying the relation of water and of salts to the electrical resistance of soils, and the departures from these simple laws will indicate other properties of soils which will be valuable in working out the chemical and physical constitution of the soils.

It is plain, from a consideration of the principles of the electrical properties of solutions, that if a quantity of a salt solution was put into a hard rubber cell with parallel electrodes and diluted with pure water that the resistance would not be affected except as a result of further dissociation. If a small quantity of salt solution is added to the quartz sand, however, and is then diluted, the resistance continues to decrease in a regular manner until the soil is completely saturated. This shows at once a property of a soil which influences the electrical resistance of solutions, and the investigation of which has already thrown an important light upon the constitution of soils.

To study this matter further 10 cc. of a salt solution were put into the hard rubber cell. If successive portions of pure water had been added to this solution the effect on the resistance would not have been noticeable, except for the slight change due to increased dissociation

with the greater dilution. Purified quartz sand, however, was put into the solution in portions of 10 grams each. The resistance immediately began to rise. With 30 grams of sand the solution was just absorbed, the sand being completely saturated. The resistance at this point was 50 per cent greater than for the solution without the sand. The successive portions of 10 grams of soil added beyond this point increased the resistance, each portion having just the same effect as any other. The effect was cumulative, so that the total resistance after 220 grams of soil had been added was about fifteen times greater than the resistance of the solution before any sand had been added. At this time there was 4.5 per cent of water in the sand. These results are shown in the accompanying table. Ten centimeters of solution were used in each case and were thoroughly mixed with different quantities of sand, as shown in the second column. The third column shows the per cent of moisture, the fourth column shows the actual resistance, the next column shows the ratio, taking the resistance of the solution as one, while the last column gives the increase in resistance for each 10 grams of sand added.

Influence of quartz sand on the electrical resistance of a salt solution.

Solution.	Sand.	Moisture.	Actual resistance.	Ratio.	Differences.*
cc.	Grams.	Per cent.	Ohms.		
10	0	33.3	171	1	0
10	30	25.0	259	1.51	0.51
10	40	16.7	350	2.05	0.54
10	60	12.5	580	3.39	0.67
10	80	10.0	795	4.65	0.65
10	1, 00	8.3	933	5.46	0.41
10	1, 20	7.1	1, 292	7.55	0.54
10	1, 40	5.5	1, 477	8.63	0.54
10	1, 80	4.5	1, 910	11.17	0.64
10	2, 20		2, 530	14.91	0.94

* For each 10 grams of sand added beyond 30.

When these results are plotted, using the resistance for the ordinates and the grams of sand as the abscissæ, they form a straight line from the initial resistance of the solution to the point where it is fully absorbed in the sand and then another straight line with a different inclination throughout the range of the experiment. This is shown in the accompanying illustration (fig. 6).

INFLUENCE OF THE TEXTURE OF SOILS UPON THE ELECTRICAL RESISTANCE.

It appears evident from the results just given that the curvature of the solid grains of soil has the effect of lengthening the path between the electrodes and so of increasing the resistance between the electrodes. This would account for the increased resistance of 50 per cent when the sand was completely saturated with solution. Also the thickness of the films around the grains would play an important part in influencing the electrical resistance of soils short of saturation.

To test the first proposition one of the hard rubber cells was filled half full with a salt solution and the resistance taken. A glass marble was then introduced which would just fit into the cell. This sphere in touching the bottom and sides of the cube left about 50 per cent by volume of space in the cell. The liquid therefore rose so as to completely fill the cell and just cover the marble. This increased the resistance on the average from 35 to 45 per cent as the result of a number of trials. When several smaller marbles were put into the cell and symmetrically arranged they had the same influence on the resistance as a single large marble, and it is evident that a thousand balls sym-

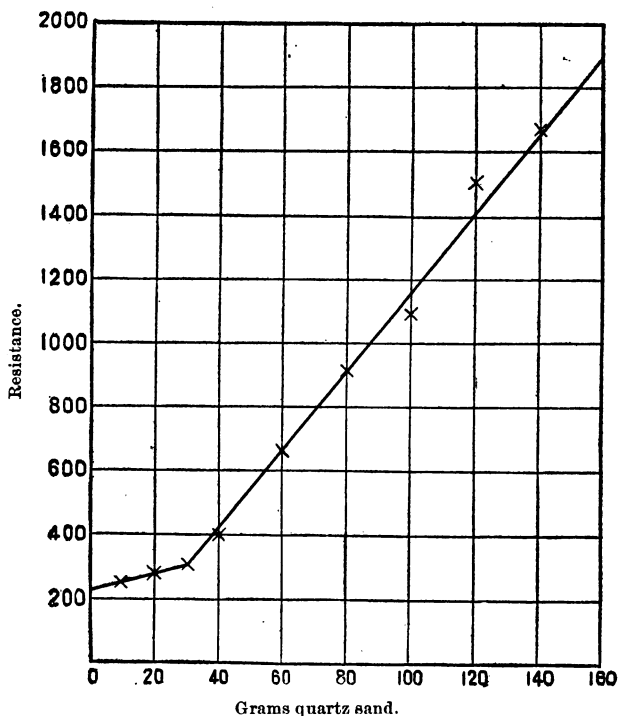


FIG. 6.—Influence of quartz sand on the electrical resistance of a salt solution.

metrically arranged which just filled the cell would have the same effect on the resistance of the solution as a single one of the larger size. This, therefore, accounts for the increase of 50 per cent in the resistance of the solution when sufficient quartz sand was introduced to just absorb it.

To investigate the matter further a soap solution was made up after the well-known formula of Plateau, composed of pure water, castile soap, and glycerin. A quantity of this was put into a hard rubber cell and the resistance taken. Some of the solution was then beaten up into a fine foam with an egg-beater and a quantity of the foam equal in weight to the solution was put into the cell, when it was found that

the resistance of the foam was about 30 or 40 per cent greater than the resistance of the solution.

It has been noticed that a fine-grained clay soil has a very much higher resistance with the same percentage of water than a coarse-grained sandy soil. In order to see if the texture of the soil really has an influence upon the resistance, the specific resistance and the salt content of several soils and mixtures of soils having very different textures were determined. An amount of soluble salt was then added to each soil to make a uniform amount of salt in the soils. The specific resistance was then determined. The soils had the same salt content and the same water content, the only difference being in the texture. This investigation was made with approximately 12 per cent of water in all the soils and also with all the soils saturated with water. The results are given in the accompanying tables:

Influence of the texture of soils containing approximately 12 per cent of water and a uniform salt content upon the electrical resistance.

Soil.	Per cent moisture.	Salt in 1 gram soil.	Specific resistance (1 cc. soil = 1.33 grams).	
			Natural soil.	Uniform salt in all soils. <i>a</i>
Early truck, Maryland	10.86	mg. 0.1021	20,110	4,080
Three parts early truck, Maryland	11.64	.1695	20,830	7,190
One part limestone, Virginia	11.81	.2051	29,360	9,000
Two parts early truck, Maryland				
One part limestone, Virginia				
Limestone, Pennsylvania	11.44	.3628	22,900	14,440
Limestone, Kentucky	11.67	.2255	26,030	14,820
Limestone, Virginia	12.10	.4204	72,180	40,670

Soil.	Surf. area 1 gram soil. <i>b</i>	Thickness of film of water. <i>c</i>	Increase temp. of mixt. <i>d</i>	Ratio.		
				Increase in temp.	Surf. area.	Sp. res.
Early truck, Maryland	Sq. cm. 600	mm. 0.0001811	° F. 0.11	4	15	28
Three parts early truck, Maryland	2,212	.0000526	2.08	72	54	50
One part limestone, Virginia						
Two parts early truck, Maryland						
One part limestone, Virginia	2,749	.0000430	2.12	74	67	62
Limestone, Pennsylvania	4,089	.0000280	2.87	106	100	100
Limestone, Kentucky	4,339	.0000269	3.68	128	106	103
Limestone, Virginia	7,048	.0000172	4.87	170	172	282

a For this determination sufficient salt was added to each soil to make a uniform content of 0.5 mg. of soluble salt per gram of soil.

b Calculated from the mechanical analyses by formula given in Weather Bureau Bulletin No. 4.

c Assuming that the actual amount of water present in the soil as shown in the first column was spread on a plane surface equal in extent to the total surface area of the soil grains in 1 gram of soil.

d Method of Gore, see next page.

Influence of the texture of soils containing a uniform salt content and saturated with water upon the electrical resistance.

Soil.	Wt. soil to 10 cc. water.	Salt in 1 gram soil.	Actual resist- ance.	Resist- ance calc. <i>a</i>	Res. soil: 10 cc. sol=1.6
		mg.			
Early truck, Maryland.....	48.7	0.1520	480	399	1.48
Three parts early truck, Maryland.....	33.2	.2068	498	477	1.77
One part limestone, Virginia.....	30.8	.2932	502	496	1.84
Two parts early truck, Maryland.....					
One part limestone, Virginia.....	24.1	.2838	498	554	2.06
Limestone, Pennsylvania.....	20.5	.2356	470	563	2.09
Limestone, Kentucky.....	15.6	.6731	490	699	2.56
Limestone, Virginia.....					

a On basis of 30 grams soil and uniform salt content.

b The solution contained in each case 3.968 mg. of salt per cubic centimeter. This was equal to the actual amount of salt in the soil and the amount added to make up to a uniform quantity in each case. The resistance of 10 cc. of NaCl solution of this strength in the cell used was 270 ohms.

With the same water and salt content the specific resistance of the fine-grained limestone soil, containing upward of 60 per cent of clay, when saturated with water was nearly twice as great as the resistance of the early truck soil containing less than 5 per cent of clay. When the soils contained approximately 12 per cent of water the resistance of the limestone soils containing the same amount of soluble salt and the same amount of water was ten times greater than the resistance of the early truck. To see if the influence in specific resistance with 12 per cent of moisture was proportional to the difference in texture the following calculations were made. The approximate surface area of the grains in 1 gram of soil was calculated from the mechanical analysis by a formula given in Weather Bureau Bulletin No. 4. It is seen that when the soils are arranged in the order of the specific resistances with a uniform salt content they are also arranged in the order of the surface area. The relative extent of surface area of the grains was next determined by a method described by Gore.¹ One hundred grams of soil, with the lumps thoroughly rubbed down, were carefully poured, with proper precautions, into 50 cc. of water at the same temperature into which the bulb of a sensitive thermometer dipped which could be read to 1-100 degree Centigrade. As the liquid spreads over the surface of the grains, a rise in temperature occurs which is proportional to the surface of the soil grains. The rise in temperature under these conditions is given in the table for the several soils. Taking the limestone soil from Pennsylvania as a unit, the ratio of the increase of temperature, the surface area, and the specific resistance show a general agreement which is certainly very striking.

In studying the influence of texture on the electrical resistance it is not necessary to actually adjust the salt content to a uniform value, as the resistance may be calculated for any other salt content if the resist-

¹Change of temperature caused by contact of liquid with powdered silica, etc. G. Gore Phil. Mag., vol. 37, 1894, pp. 306-316.

ance for a certain content is known. This is done by the use of the following formula:

$$R_u = \frac{R S}{S_u},$$

where R_u = resistance of soil with unit quantity salt; R = resistance of natural soil; S = salt in natural soil; S_u = unit quantity salt, usually .5 mg. per gram.

It is evident that the size of the capillary spaces in a saturated soil and the thickness of the film of water around the soil grains when the soil is short of saturation have a marked influence upon the resistance of the soil.

If the amount of water present in the soils containing 12 per cent by weight was uniformly spread over an area equal to the estimated area of the soil grains, in each case the thickness of the film as given in the table would be comparable to the thickness of the thinnest portion of a soap bubble when it turns black just before bursting. The films of water around the grains of a moist soil are thus so exceedingly thin that they lose the properties of a liquid in mass. The small capillary spaces in the soil and the thin films in soils short of saturation offer a greater resistance to the electric current than is offered by a similar solution in bulk.

If a cell were filled with pure quartz sand and salt solution was introduced from below so as to saturate a layer of soil 1 centimeter deep and the solution was prevented from spreading, it would seem at first sight as though the resistance should be the same as though the same quantity of solution was uniformly mixed with the soil. Notwithstanding the increase in the area of the electrodes the resistance would increase on account of the higher resistance in the thin film of water around the soil grains.

As the amount of water in the soil is decreased by evaporation air spaces must form and must enlarge. Films will therefore have to break and all the films will not be continuous in the soil from one electrode to the other. If the films break *in the same way* and the solubility of the soil is not changed, any particular soil should always have the same resistance for any given percentage of water and salt content. It would seem possible that with a change in the surface tension of the soil moisture the mean thickness of the film around the grains and the way in which the films break would be somewhat affected and that this might have some influence on the resistance. This is an interesting line of investigation, which should be followed out.

REDUCTION OF ELECTRICAL RESISTANCES TO A UNIFORM TEMPERATURE.

In order to compare the electrical resistances of soils intelligently it is necessary to reduce them all to a uniform temperature. In this Division the resistances are all reduced to a temperature of 60° F.

Reduction of the electrical resistance of soils to a uniform temperature of 60° F.

°F.	1000	2000	3000	4000	5000	6000	7000	8000	9000
32.0	625	1,250	1,875	2,500	3,125	3,750	4,375	5,000	5,625
32.5	632	1,265	1,897	2,530	3,163	3,795	4,425	5,059	5,691
33.0	640	1,280	1,920	2,560	3,200	3,840	4,480	5,120	5,760
33.5	647	1,294	1,941	2,588	3,235	3,883	4,530	5,177	5,824
34.0	653	1,306	1,959	2,612	3,265	3,918	4,571	5,224	5,877
34.5	660	1,320	1,980	2,640	3,300	3,960	4,620	5,280	5,940
35.0	668	1,336	2,004	2,672	3,340	4,008	4,676	5,344	6,012
35.5	675	1,350	2,025	2,700	3,375	4,050	4,725	5,400	6,075
36.0	683	1,366	2,049	2,732	3,415	4,098	4,781	5,464	6,147
36.5	690	1,380	2,070	2,760	3,450	4,140	4,830	5,520	6,210
37.0	698	1,396	2,094	2,792	3,490	4,188	4,886	5,584	6,282
37.5	704	1,408	2,112	2,816	3,520	4,224	4,928	5,632	6,336
38.0	711	1,422	2,133	2,844	3,555	4,266	4,977	5,688	6,399
38.5	717	1,434	2,151	2,868	3,585	4,302	5,019	5,736	6,453
39.0	723	1,446	2,169	2,892	3,615	4,338	5,061	5,784	6,507
39.5	729	1,458	2,187	2,916	3,645	4,374	5,103	5,832	6,561
40.0	735	1,470	2,205	2,940	3,675	4,410	5,145	5,880	6,615
40.5	742	1,484	2,226	2,968	3,710	4,452	5,194	5,936	6,678
41.0	750	1,500	2,250	3,000	3,750	4,500	5,250	6,000	6,750
41.5	757	1,514	2,271	3,028	3,785	4,542	5,299	6,056	6,813
42.0	763	1,526	2,289	3,052	3,815	4,578	5,341	6,104	6,867
42.5	770	1,540	2,310	3,080	3,850	4,620	5,390	6,160	6,930
43.0	776	1,552	2,328	3,104	3,880	4,656	5,432	6,208	6,984
43.5	782	1,564	2,346	3,128	3,910	4,692	5,474	6,256	7,038
44.0	788	1,576	2,364	3,152	3,940	4,728	5,516	6,304	7,092
44.5	794	1,588	2,382	3,176	3,970	4,764	5,558	6,352	7,146
45.0	800	1,600	2,400	3,200	4,000	4,800	5,600	6,400	7,200
45.5	807	1,614	2,421	3,228	4,035	4,842	5,649	6,456	7,263
46.0	814	1,628	2,442	3,256	4,070	4,884	5,698	6,512	7,326
46.5	821	1,642	2,463	3,284	4,105	4,926	5,747	6,568	7,389
47.0	828	1,656	2,484	3,312	4,140	4,968	5,796	6,624	7,452
47.5	835	1,670	2,505	3,340	4,175	5,010	5,845	6,680	7,515
48.0	843	1,686	2,529	3,372	4,215	5,058	5,901	6,744	7,587
48.5	850	1,700	2,550	3,400	4,250	5,100	5,950	6,800	7,650
49.0	856	1,712	2,568	3,424	4,280	5,136	5,992	6,848	7,704
49.5	862	1,724	2,586	3,448	4,310	5,172	6,034	6,896	7,758
50.0	867	1,734	2,601	3,468	4,335	5,202	6,069	6,936	7,803
50.5	874	1,748	2,622	3,496	4,370	5,244	6,118	6,992	7,866
51.0	881	1,762	2,643	3,524	4,405	5,286	6,167	7,048	7,929
51.5	887	1,774	2,661	3,548	4,435	5,322	6,209	7,096	7,983
52.0	893	1,786	2,679	3,572	4,465	5,358	6,251	7,144	8,037
52.5	900	1,800	2,700	3,600	4,500	5,400	6,300	7,200	8,100
53.0	906	1,812	2,718	3,624	4,530	5,436	6,342	7,248	8,154
53.5	912	1,824	2,736	3,648	4,560	5,472	6,384	7,296	8,208
54.0	917	1,834	2,751	3,668	4,585	5,502	6,419	7,336	8,253
54.5	925	1,850	2,775	3,700	4,625	5,550	6,475	7,400	8,325
55.0	933	1,866	2,799	3,732	4,665	5,598	6,531	7,464	8,397
55.5	940	1,880	2,820	3,760	4,700	5,640	6,580	7,520	8,460
56.0	947	1,894	2,841	3,780	4,735	5,682	6,629	7,576	8,523
56.5	954	1,908	2,862	3,816	4,770	5,724	6,678	7,632	8,586
57.0	961	1,922	2,883	3,844	4,805	5,766	6,727	7,688	8,649
57.5	968	1,936	2,904	3,872	4,839	5,807	6,775	7,743	8,711
58.0	974	1,948	2,922	3,896	4,870	5,844	6,818	7,792	8,766
58.5	981	1,961	2,942	3,923	4,903	5,884	6,864	7,845	8,826
59.0	987	1,974	2,962	3,949	4,936	5,923	6,910	7,898	8,885
59.5	994	1,988	2,982	3,976	4,971	5,965	6,959	7,953	8,947
60.0	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000
60.5	1,006	2,013	3,019	4,026	5,032	6,039	7,045	8,052	9,059
61.0	1,013	2,026	3,039	4,052	5,065	6,078	7,091	8,104	9,117
61.5	1,020	2,040	3,060	4,080	5,100	6,120	7,140	8,160	9,180
62.0	1,027	2,054	3,081	4,108	5,135	6,162	7,189	8,216	9,243
62.5	1,033	2,067	3,100	4,134	5,167	6,201	7,234	8,268	9,302
63.0	1,040	2,080	3,120	4,160	5,200	6,240	7,280	8,320	9,360
63.5	1,047	2,094	3,141	4,188	5,235	6,282	7,329	8,376	9,423
64.0	1,054	2,108	3,162	4,216	5,270	6,324	7,378	8,432	9,486
64.5	1,060	2,121	3,181	4,242	5,302	6,363	7,423	8,484	9,545
65.0	1,067	2,134	3,201	4,268	5,335	6,402	7,469	8,536	9,603
65.5	1,074	2,148	3,222	4,298	5,370	6,444	7,518	8,592	9,666

Reduction of the electrical resistance of soils to a uniform temperature of 60° F.—Cont'd.

°F.	1000	2000	3000	4000	5000	6000	7000	8000	9000
66.0	1,081	2,162	3,243	4,324	5,405	6,486	7,567	8,648	9,729
66.5	1,088	2,176	3,264	4,352	5,440	6,528	7,616	8,704	9,792
67.0	1,095	2,190	3,285	4,380	5,475	6,570	7,665	8,760	9,855
67.5	1,102	2,205	3,307	4,410	5,512	6,615	7,717	8,820	9,922
68.0	1,110	2,220	3,330	4,440	5,550	6,660	7,770	8,880	9,990
68.5	1,117	2,235	3,352	4,470	5,587	6,705	7,823	8,940	10,058
69.0	1,125	2,250	3,375	4,500	5,625	6,750	7,875	9,000	10,125
69.5	1,133	2,265	3,398	4,530	5,663	6,795	7,928	9,060	10,193
70.0	1,140	2,280	3,420	4,560	5,700	6,840	7,980	9,120	10,260
70.5	1,147	2,295	3,442	4,590	5,737	6,885	8,032	9,180	10,327
71.0	1,155	2,310	3,465	4,620	5,775	6,930	8,085	9,240	10,395
71.5	1,162	2,325	3,487	4,650	5,812	6,975	8,137	9,300	10,462
72.0	1,170	2,340	3,510	4,680	5,850	7,020	8,190	9,360	10,530
72.5	1,177	2,355	3,532	4,710	5,887	7,065	8,242	9,420	10,597
73.0	1,185	2,370	3,555	4,740	5,925	7,110	8,295	9,480	10,665
73.5	1,193	2,386	3,579	4,772	5,965	7,158	8,351	9,544	10,737
74.0	1,201	2,402	3,603	4,804	6,005	7,206	8,407	9,608	10,809
74.5	1,208	2,416	3,624	4,832	6,040	7,248	8,456	9,664	10,872
75.0	1,215	2,430	3,645	4,860	6,075	7,290	8,505	9,720	10,935
75.5	1,222	2,445	3,667	4,890	6,112	7,335	8,557	9,780	11,002
76.0	1,230	2,460	3,690	4,920	6,150	7,380	8,610	9,840	11,070
76.5	1,237	2,475	3,712	4,950	6,187	7,425	8,662	9,900	11,137
77.0	1,245	2,490	3,735	4,980	6,225	7,470	8,715	9,960	11,205
77.5	1,253	2,506	3,759	5,012	6,265	7,518	8,771	10,024	11,277
78.0	1,261	2,522	3,783	5,044	6,305	7,566	8,827	10,088	11,349
78.5	1,269	2,538	3,807	5,076	6,345	7,614	8,883	10,152	11,421
79.0	1,277	2,554	3,831	5,108	6,385	7,662	8,939	10,216	11,493
79.5	1,285	2,576	3,856	5,142	6,427	7,713	8,998	10,284	11,569
80.0	1,294	2,598	3,882	5,176	6,470	7,764	9,058	10,352	11,646
80.5	1,302	2,609	3,906	5,208	6,510	7,812	9,114	10,416	11,718
81.0	1,310	2,620	3,930	5,240	6,550	7,860	9,170	10,480	11,790
81.5	1,318	2,637	3,955	5,274	6,592	7,911	9,229	10,546	11,866
82.0	1,327	2,654	3,981	5,308	6,635	7,962	9,289	10,616	11,943
82.5	1,335	2,670	4,005	5,340	6,675	8,010	9,345	10,680	12,015
83.0	1,343	2,686	4,029	5,372	6,715	8,058	9,401	10,744	12,087
83.5	1,351	2,702	4,053	5,404	6,755	8,106	9,457	10,808	12,159
84.0	1,359	2,718	4,077	5,436	6,795	8,154	9,513	10,872	12,231
84.5	1,367	2,735	4,102	5,470	6,837	8,205	9,572	10,940	12,307
85.0	1,376	2,752	4,128	5,504	6,880	8,256	9,632	11,008	12,384
85.5	1,385	2,769	4,153	5,538	6,922	8,307	9,691	11,076	12,460
86.0	1,393	2,786	4,179	5,572	6,965	8,358	9,751	11,144	12,537
86.5	1,401	2,802	4,203	5,604	7,005	8,406	9,807	11,208	12,609
87.0	1,409	2,818	4,227	5,636	7,045	8,454	9,863	11,272	12,681
87.5	1,418	2,836	4,254	5,672	7,090	8,508	9,921	11,344	12,762
88.0	1,427	2,854	4,281	5,708	7,135	8,562	9,989	11,416	12,843
88.5	1,435	2,870	4,305	5,740	7,175	8,610	10,040	11,480	12,915
89.0	1,443	2,886	4,329	5,772	7,215	8,658	10,091	11,544	12,987
89.5	1,451	2,903	4,354	5,806	7,257	8,709	10,155	11,612	13,063
90.0	1,460	2,920	4,380	5,840	7,300	8,760	10,220	11,680	13,140
90.5	1,468	2,937	4,405	5,874	7,342	8,811	10,279	11,748	13,216
91.0	1,477	2,954	4,431	5,908	7,385	8,862	10,339	11,816	13,293
91.5	1,486	2,972	4,458	5,944	7,430	8,916	10,402	11,888	13,374
92.0	1,495	2,990	4,485	5,980	7,475	8,970	10,465	11,960	13,455
92.5	1,504	3,008	4,512	6,016	7,520	9,024	10,528	12,032	13,536
93.0	1,513	3,026	4,539	6,052	7,565	9,078	10,591	12,104	13,617
93.5	1,522	3,045	4,567	6,090	7,612	9,135	10,657	12,180	13,702
94.0	1,532	3,064	4,596	6,128	7,660	9,192	10,724	12,256	13,788
94.5	1,541	3,083	4,624	6,166	7,707	9,249	10,790	12,332	13,873
95.0	1,551	3,102	4,653	6,204	7,755	9,306	10,857	12,408	13,959
95.5	1,560	3,121	4,681	6,242	7,802	9,363	10,923	12,484	14,040
96.0	1,570	3,140	4,710	6,280	7,850	9,420	10,990	12,560	14,130
96.5	1,580	3,160	4,740	6,320	7,900	9,480	11,060	12,640	14,220
97.0	1,590	3,180	4,770	6,360	7,950	9,540	11,130	12,720	14,310
97.5	1,600	3,201	4,801	6,402	8,002	9,603	11,203	12,804	14,404
98.0	1,611	3,222	4,833	6,444	8,055	9,666	11,277	12,888	14,499
98.5	1,620	3,240	4,860	6,480	8,103	9,720	11,340	12,960	14,580
99.0	1,629	3,258	4,887	6,516	8,145	9,774	11,403	13,032	14,661

This reduction can readily be made by the use of the preceding table, which has been calculated from the temperature coefficient of nine types of soil described in Bulletin No. 7.

A single illustration will serve to show the way this table is used. Suppose the observed resistance of the soil is 2,585 ohms at a temperature of 50.5°. In the table at the temperature of 50.5°, as indicated on the left-hand side, we find that at that temperature 2,000 ohms is equal to 1,748 ohms at 60°; 500 ohms is equal to 437 ohms at 60°, hence 500 ohms would be equal to 437 ohms. Similarly 80 ohms would be one-hundredth of the value given for 8,000 ohms at 50.5° in the table, therefore, equal to about 70 ohms at 60°; while the 5 ohms would be equal to about 4 ohms. These separate values are added together thus:

2,000	1,748
500	437
80	70
5	4

$$2,585 \text{ ohms at } 50.5^\circ = 2,259 \text{ ohms at } 60^\circ$$

The table is constructed only for intervals of 0.5° F. Ordinarily this is close enough. A temperature between a whole degree and a half degree, more or less, is either increased or diminished, so as to make it a whole degree or a half degree. If it is desired to work closer than this it can be done by interpolation in the table.



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